IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012073 doi:10.1088/1757-899X/1344/1/012073

# LCLS-II Cryoplant Operational Availability: 3 Years of Operation

**S. Vyawahare*, E. Fauve, V. Ravindranath, A. Apte, B. Rama, S. Shrishrimal, M. Keenan, F. Moguel, J. Pucci**

SLAC, 2575 Sand Hill Road, Menlo Park, CA-94025, US

*Email:- saeev@slac.stanford.edu

**Abstract.** The LCLS-II X-ray light source at Stanford National Accelerator Laboratory, powered by a 700 meter superconducting LINAC, is supported by two 4 kW @ 2.0 K cryoplants. The first cryoplant (CP), commissioned in 2021, successfully cooled the LINAC in April 2022. This paper provides a detailed analysis of the cryoplant's operational performance and reliability over the subsequent 3 years of continued operation. Key metrics, including Mean Time Between Failures (MTBF), Mean Time To Recover (MTTR) are evaluated along with semi-annual data. The paper also highlights operational challenges, and the strategies implemented to enhance system availability and reduce downtime. These insights aim to guide the design and operation of future large-scale cryogenic systems, with a focus on improving availability and reliability.

## 1. Introduction

The Linac Coherent Light Source II (LCLS-II) is an advanced X-ray free-electron laser facility at the SLAC National Accelerator Laboratory located in Menlo Park, California. It is a 4 GeV continuous wave linear accelerator (LINAC) that generates incredibly bright, ultrafast X-ray pulses up to 1 million times per second. The LCLS-II LINAC consists of 37 cryomodules that operate at 2.0 K temperatures provided by the cryoplant. Figure.1 shows the cryoplant and the LINAC which constitutes the cryogenic system.

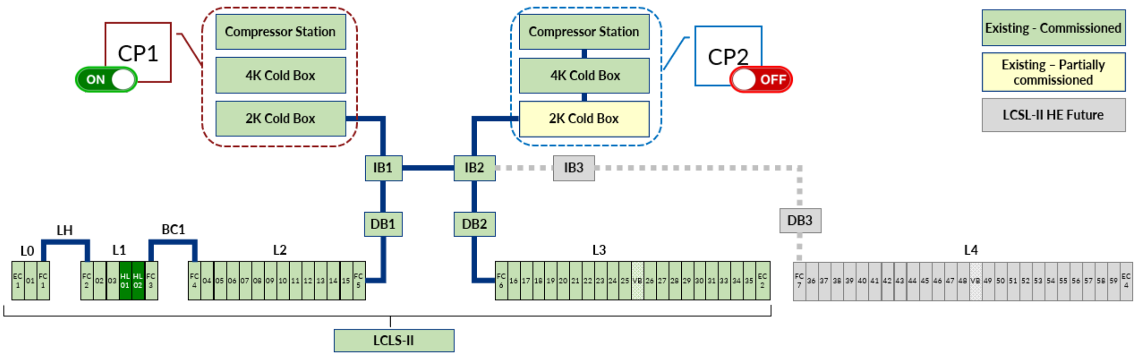


**Figure 1.** SLAC LCLS-II Cryogenic System Overview

The LCLS-II facility relies on two powerful cryogenic cooling plants, each with a cooling capacity of 18 kW equivalent at 4.5 K including 4.0 kW at 2.0 K [1]. Cryoplant #1 (CP1) was initially cooldown to 2 K in April 2022. Cryoplant #2 (CP2) commissioning was completed in September 2023.

At present, the LCLS-II LINAC operates solely on CP1, which provides all necessary cooling. CP2 is currently inactive and scheduled to resume operation in 2027 as part of the planned LCLS- II High Energy (LCLS-II HE) enhancement. This future upgrade will introduce 23 supplementary cryomodules to the system, effectively doubling the beam energy capacity from 4 GeV to 8 GeV.

This study examines the performance of CP1 throughout its three-year operational period from March 2022 till May 2025. By sharing availability data and operational metrics such as MTBF and MTTR, this paper aims to provide valuable insights for similar large scale cryogenic facilities facing comparable technical challenges.

## 2. Availability: Concepts and Definitions

Availability of a system, in this case - the cryoplant, is its ability to deliver the required mode of operation during a defined time span. There are two different availability numbers:

- $\mathbf{A_0}$: Operational availability, availability considering internal and external factors.
- $\mathbf{A_i}$: Inherent availability, availability considering internal factors only.

$A_0$, operational availability measures a system's total uptime by accounting for both internal and external downtime factors. Internal factors, such as malfunctioning cryoplant equipment, 2 K cold compressors or turbines, etc. directly impact system reliability. External factors, including electrical power loss, instrument air loss or cooling water unavailability, etc. reduce uptime despite being outside the system's inherent design.

$A_i$, inherent availability focuses exclusively on system reliability related to internal equipment failures, providing a measure of the equipment's intrinsic dependability without considering external utility interruptions. This distinction helps to differentiate between equipment design issues and operational environment challenges when analysing system performance.

MTBF represents the average operational duration between consecutive system failures, providing a comprehensive measure of overall reliability. This critical metric encompasses all failure events regardless of their origin—whether stemming from internal factors or external factors. MTBF offers a holistic view of how frequently the cryoplant experiences interruptions under real-world conditions.

MTTR quantifies the average duration required to restore system functionality following any failure event. This metric captures the entire recovery process—from fault detection and diagnosis through repair implementation and system restart until normal operational parameters are achieved. MTTR serves as a direct indicator of maintenance efficiency, emergency response effectiveness, and system resilience. Lower MTTR values reflect superior troubleshooting protocols, availability of spare parts, staff expertise, and system design that facilitates rapid recovery, ultimately minimizing the impact of inevitable failures on overall system availability.

*2.1 Cryoplant : Modes of operation*

Evaluating availability of a system is highly dependent on the data behind it. Clean data comes from a good understanding of the different operating modes of the cryoplant. The operating modes of the cryoplant and the LINAC considered for this study are defined below in Table 1.

**Table 1.** Cryoplant and LINAC operating modes

| Cryoplant | Status | Definition |
|---|---|---|
| 2 K Mode | Available | Cryoplant is at 2 K |
| 4 K Mode | Available | Cryoplant is at 4 K and ready to delivery 2 K Mode |
| 4 K Only Mode | Not Available | Cryoplant is at 4 K , but unable to operate at 2 K Mode |
| Recovery | Not Available | Cryoplant is in recovery after a trip until 4 K stable operation. This covers all recovery steps from trip event to 4 K stable operation |
| **LINAC** | **Status** | **Definition** |
| 2 K Mode | Available | LINAC is at 2 K as scheduled |
| 4 K Mode | Available | LINAC is at 4 K as scheduled |
| Recovery | Not available | LINAC is not operating as scheduled |

## 3. Cryoplant Availability: Overview

Over three years of operation the cryoplant achieved an inherent availability of 97%. The target inherent availability for the cryoplant was set at 98.62% based on observations from other laboratories [2]. Figure 2 illustrates the operational states distribution for both the cryoplant and

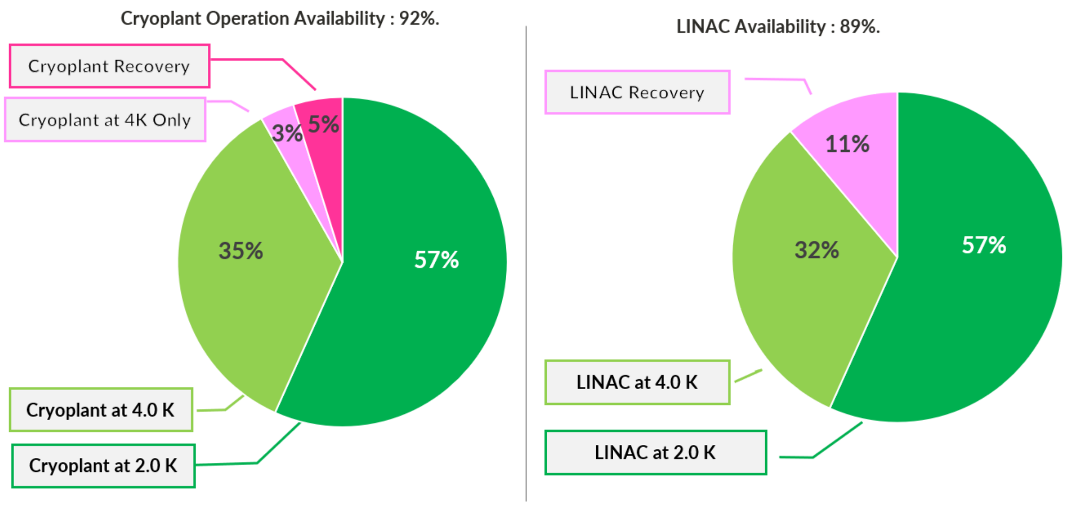


**Figure 2.** LCLS-II Cryoplant Availability : Mar. 2022-May 2025 [1162 days of continued operation]

LINAC. Cryoplant operational availability was 92% and LINAC availability was 89%. The lower LINAC availability reflects the additional complexity involved in returning the LINAC to operational status following disruptions. LINAC longer MTTR includes LINAC 2 K pump-down and fast cool-down [3] resulting in shorter uptime and lower availability, approximately 3% less than cryoplant. Other key metrics are given in Table 2.

**Table 2.** Key metrics : 3 years of operation

| Key Metrics | Cryoplant | LINAC |
|---|---|---|
| Operational Availability, $A_0$ | 92% | 89% |
| Inherent Availability, $A_i$ | 97% | - |
| MTBF | 40 days | 38 days |
| MTTR | 3 days | 5 days |
| Total uptime | 1075 days | 1032 days |
| Total downtime | 87 days | 130 days |
| Total no. of faults | 27 | 27 |

[a] 3 years of operation data spans 1162 days from March 2022 till May 2025 (partial May)

3.*1 Cryoplant* unavailability

Over the three-year operational period, cryoplant experienced a total of 87 days of downtime resulting from 27 distinct fault events. Notably, utility-related issues dominated the downtime landscape, accounting for 62% of all unavailability, with electrical problems being particularly significant—contributing approximately 1,300 hours (53 days) of downtime across 9 separate fault incidents. Other utility failures such as cooling water problem, instrument air failures and network failure added together contributed 20 hours in downtime. Figure 3 shows the cryoplant downtime with fault type.

Within the cryogenic system, representing 38% of total downtime, 2 K cold compressor (2 K CC) drives emerged as the leading cause with around 450 hours (19 days) of downtime from 9 fault occurrences related to 2 K CC electronics. Other cryogenic contributors included turbine failures (approximately 200 hours), instrumentation issues (about 100 hours), and minimal impact from helium compressor sight glass issues and human error.

The distribution pattern indicates that the cryogenic components such as cold compressors and turbines are crucial for availability. External utilities such as electrical power, constitutes a significant challenge to ensuring uninterrupted cryoplant performance. Cooling water causes fewer outages but remains problematic despite redundant cells (4+1) and pumps (2+1). Persistent issues with water chemistry, corrosion, and filter clogging require frequent maintenance making it a major concern.

IOP Conf. Series: Materials Science and Engineering **1344** (2026) 012073 doi:10.1088/1757-899X/1344/1/012073

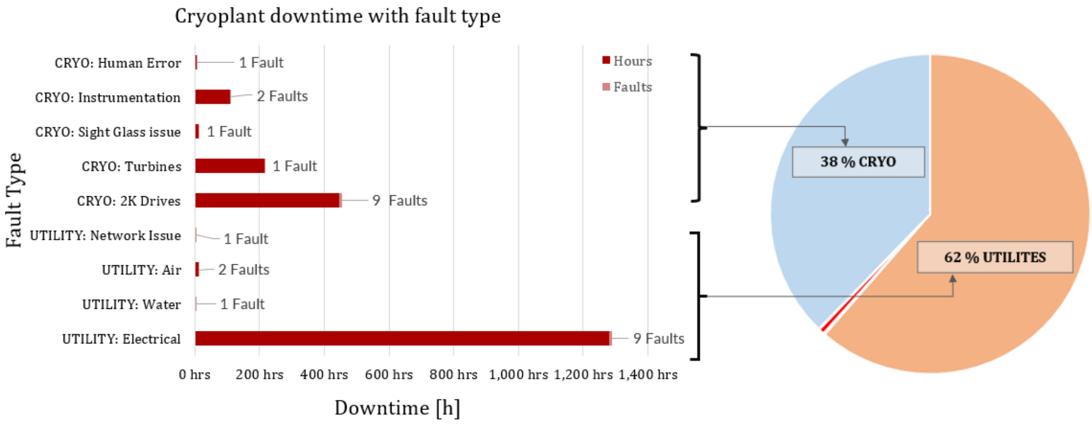


**Figure 3.** Cryoplant downtime with fault type

## *3.2 Semi-annual data*

The semi-annual data provides a deeper understanding of the cryoplant's performance across three critical metrics—cryoplant availability, MTBF, and MTTR. This time scale perspective allows sufficient data points to distinguish between statistical anomalies and genuine reliability concerns. Examining key performance indicators at 6-month intervals shows impact of implemented improvements and can help develop realistic projections for future operational planning and resource allocation.

## *3.3 Cryoplant availability*

Figure 4 shows the availability of the system for each of the 6 semi-annual periods. The cryoplant maintained an operational availability averaging 92%. A dramatic drop to 71% during semi-annual period 3 due to a 24-hour power outage highlights the system's vulnerability to utility disruptions despite its otherwise consistent performance.

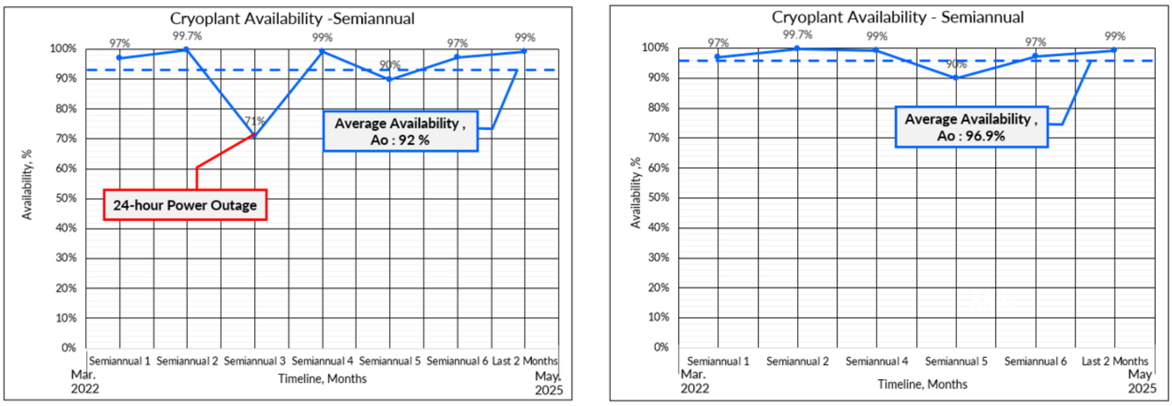


**Figure 4.** Cryoplant availability (a) semi-annual data (b) semi-annual data excluding the outlier data point of semi-annual 3

It is interesting to note that if we exclude the 71% anomaly from semi-annual 3, the average operational availability would be approximately 96.9%. This calculation takes the average of the remaining values which provides a more representative measure of the system's typical performance under normal operating conditions without the significant utility disruption.

*3.4 MTBF*

Figure 5 Cryoplant MTBF semi-annual data shows the longest run between two trips was 56 days in semi-annual period 2 before declining due to utility disruptions, power and water (semi-annual period 3 & semi-annual period 4) and recurring 2 K cold compressor failures stemming from Variable Frequency Drive (VFD) and Active Magnetic Bearing (AMB) issues (semi-annual period 5 & semi-annual period 6). The frequency of system trips far exceeded original projections, with the majority occurring during off-hours. Based on this operational reality, the cryogenics team maintained the 24/7 staffing model originally implemented only for the commissioning phase. The final period reported represents only two months of data instead of a full 6 Month period.

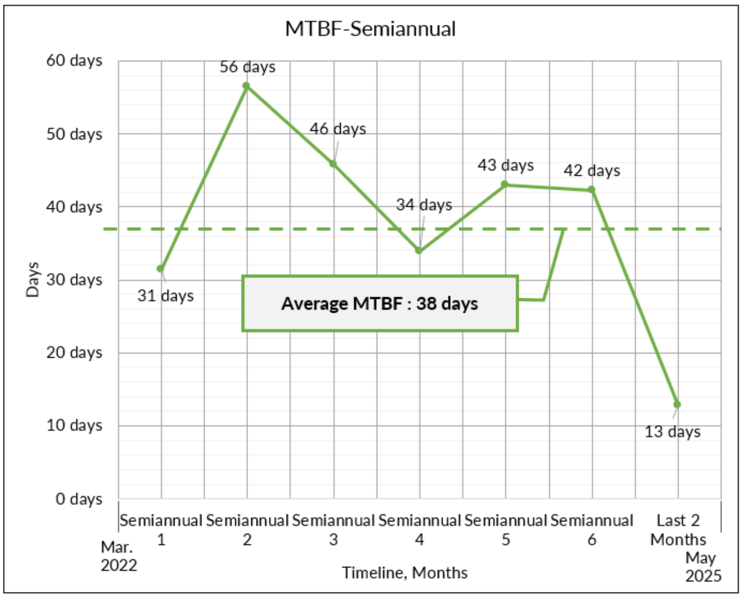


**Figure 5.** MTBF – semi-annual data

*3.5 MTTR*

The MTTR data in Figure 6 reveals considerable variation across semi-annual periods, with a sudden spike to 450 hours in period 3 corresponding to the major power outage event. Despite this outlier, the system generally demonstrates efficient recovery capabilities with most periods showing MTTR values between 8-24 hours, resulting in an overall average of 97 hours—though this average is heavily skewed by the single exceptional downtime incident.

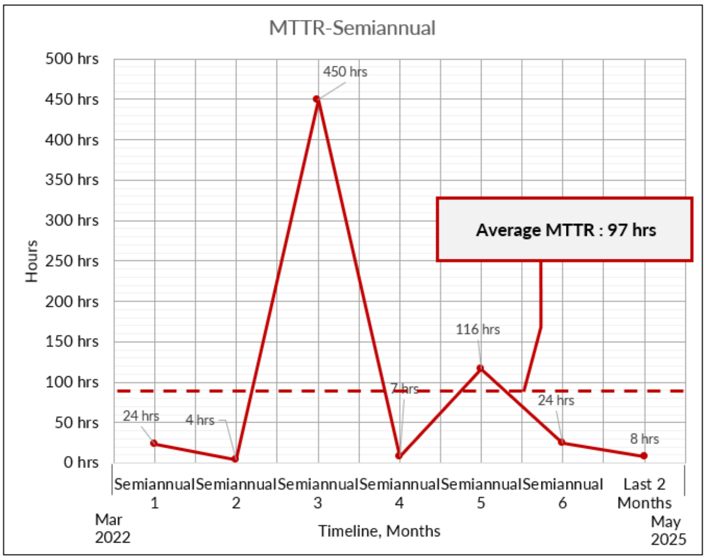


**Figure 6.** MTTR – semi-annual data

## 4. Cryoplant comprehensive response

The LCLS-II cryoplant operates under a robust 24/7/365 operational framework and employs a comprehensive strategy that ensures continuous operation and swift recovery from disruptions to maximize availability.

*4.1 System design*
*System automation:* Advanced control systems enable automatic response to operational variations, implement protective measures during anomalies, and maintain optimal process parameters with minimal human intervention.
*Redundancy:* Each cryogenic plant has a set of five operating warm compressors plus an additional standby compressor that can be used in place of any other compressor, providing crucial redundancy[4].

*4.2 Operational planning*
*Spare parts management:* Critical capital spare parts, including turbines and cold compressors, were procured during the project, significantly reducing potential downtime during equipment failures.
*Inventory infrastructure:* A single cryoplant operation in nominal 2 K mode is supported by four helium jumbo tube trailers on-site providing 100% back-up inventory in case of emergencies. Liquid Nitrogen (LN2) storage provides LN2 supply for approximately 25 days of operation.
*Procedures development:* System reliability is further enhanced through well-established emergency procedures with physical documentation readily available in the control room, regularly reviewed and updated, and a dedicated alarm handling application for immediate notification.

*4.3 Execution strategy*
*Manned operation:* Operations are structured around three 8-hour shifts with trained personnel responsible for maintaining electronic logs, continuous control room monitoring, daily plant

walkdowns, and technical process support. This front-line team is supplemented by two on-call engineers who can intervene remotely or locally as needed and respond to plant emergencies or operator queries.

All of the above strategies have contributed to the successful three-year operational record of the cryogenic system.

## 5. Summary

The LCLS-II Cryoplant demonstrated a 92% operational availability (accounting for both internal and external factors) and 97% inherent availability (reflecting only internal factors), falling short of the target benchmark of 98.62% over three years of operation. Power outages were the primary cause of downtime, followed by 2 K cold compressor failures. To address these challenges, SLAC is implementing significant power resiliency projects site wide. Comprehensive maintenance plans to reduce utility losses such as cooling water system unavailability are under development. The effectiveness of existing recovery strategies—including enhanced system automation, 24/7 staffed operations, strategic spare parts inventory, and pre-established emergency and maintenance procedures—has been validated through reduced recovery times following system trips. These operational measures will be essential to achieving target availability metrics for the LCLS-II Cryoplant in future operational years.

## Acknowledgments

This work was supported by Department of Energy contract DE-AC02-76SF00515.

## References

[1] E. Fauve et al 2024, "LCLS-II Helium Refrigeration System : A comprehensive overview of the project", IOP Conf. Ser.: Mater. Sci. Eng. 1301 012117
[2] K. Brodzinski, et.al 2017, "LHC Cryogenics – Strategy, unavailability root causes and limitations (Run 2016) "CERN, Geneva, Switzerland
[3] Shrishrimal, S., et al. (2024). LCLS-II LINAC Cooldown and Fast Cooldown ICEC29-ICMC2024
[4] V. Ravindranath et al, "LCLS-II warm helium compressor commissioning" 2022 IOP Conf. Ser.: Mater. Sci. Eng. 1240 012112